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Effects of soil frost on snowmelt runoff generation and surface water quality in drained peatlands

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Runoff generation and fluxes of dissolved elements were studied in two drained peatlands under different land uses during spring snowmelt 2012. One site experienced soil frost, whereas the other site was frost-free due to groundwater seepage. Runoff water was sampled at 12-hour intervals during the snowmelt peak and soil and snow samples were taken. All samples were analysed for oxygen-18 isotope and various water quality parameters. The results demonstrated the effect of soil frost on water flow paths, which further affected runoff water quality. At the frost-free site, seepage through the peat soil profile was the main flow route during snowmelt runoff generation, which could be seen e.g., as high DOC concentration in the stream. At the site with soil frost, meltwater could not infiltrate into the soil, leading to overland flow and lower concentrations of elements in water during the peak snowmelt period.

Introduction

In the northern hemisphere, snowmelt is a major component of the annual water balance (Laudon *et al*. 2004, Barnett *et al*. 2005, Finlay *et al*. 2006). Seasonal soil frost has been observed to affect water flow paths and the timing of maximum snowmelt runoff, but its role in controlling transport is still somewhat unclear, especially in peatland-dominated catchments. Globally, peatlands cover approximately 3% of the Earth's surface and the majority are located at high latitudes, in cold temperate regions (Gorham 1991). Drainage of peat soils has been carried out on a large scale to promote forest growth, agriculture or peat extraction. Drainage ditches lower the groundwater in the peat profile, which moves the flow path from the surface layer to deeper in the peat profile. This results in increased leaching of elements to streams (Burt 1995, Holden *et al*. 2004). Water quality problems such as low alkalinity and increased transport of suspended solids, nutrients and aluminium have typically been observed after drainage (Kenttämies 1981, Kløve 2001, Joensuu *et al*. 2001, Joensuu *et al*. 2002, Marttila and Kløve 2010, Nieminen *et al*. 2010), which may reduce downstream aquatic habitat quality (Vuori *et al*. 1998). In Finland, runoff water treatment is required for peat extraction areas in the frost-free months (May–October), but more recently also in winter and spring months.

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Visible effects of seasonal soil frost on snowmelt runoff in the form of overland flow or pooling water on top of the frozen soil have been reported in some studies (Shanley and Chalmers 1999, Ketcheson *et al*. 2012). Stähli *et al*. (2001) showed that runoff generation from snowmelt was systematically underestimated by a model without a soil frost component. High saturation conditions in soil during frost formation and rain on frozen soil strengthened the effect of soil frost on runoff generation during the snowmelt period in that study. Laudon *et al*. (2004) observed that soil frost can reduce the infiltration rate and therefore increase overland flow and quantified the share of such flow as approximately 20% of the total runoff event. A high proportion of peat soils within a catchment has been noted to increase the runoff originating from snow in total runoff during spring peak flow (Lepistö 1995, Laudon *et al*. 2007).

Information about snowmelt runoff generation is important for planning efficient water treatment policies for peat extraction, peatland forestry and agriculture. The starting hypothesis in this study was that soil frost changes flow paths in ways which are reflected in water quality, as soil frost limits the interaction between meltwater and soil. This hypothesis is supported by Iwata *et al*. (2010), who noted that frozen soil affects the flow path of meltwater mainly by constraining infiltration, which can lead to more runoff generation as overland flow. The influence of frost on runoff generation is also relevant in climate change impact studies.

In this study, we examined differences in the quality, quantity and timing of runoff water from peatland areas with different land use types (peat extraction, forestry) during the snowmelt period. The sites were chosen based on their different soil frost conditions, as the peatland forestry area is influenced by groundwater discharge, thus warming the soil and resulting in less frost than the peat extraction area. Specific objectives were to: (i) determine the amount of runoff generated, (ii) quantify the amounts of elements transported from drained peatlands during the snowmelt period, and (iii) study the effect of soil frost on runoff and element fluxes. The overall aim was to gain a better understanding of regional differences in snowmelt runoff generation from peatlands.

Material and methods

Study sites

The selected study areas were located in the Oulujoki catchment (~65°N, 26°E) in northern Finland, where the permanent snow cover lasts for approximately 160–175 days, mean annual temperature is +2 °C and mean annual precipitation is approximately 500 mm (data from the Finnish Meteorological Institute). On average, the permanent snow cover starts between 16 and 26 November and ends between 20 and 30 April (data from the Finnish Meteorological Institute). Maximum snow thickness in the region during the years 1981–2010 varied between 40 and 60 cm (data from the Finnish Meteorological Institute) and mean annual maximum snow water equivalent (SWE) was 166 mm (data from the OIVA database of Finland's Environment Administration). SWE was measured at the nearby Vaala-Oulujärvi location by SYKE (Finnish Environment Institute) from 1946 to 2013, during which period the maximum SWE was usually observed in April (data from the OIVA database of Finland's Environment Administration). On average, soil frost can extend to 40 cm depth (or more in open areas) (Soveri and Varjo 1977, Korhonen and Haavanlammi 2012). In terms of topography, the region is fairly flat, with most of the area being less than 200 m a.s.l. (Tikkanen 1994).

In Korentosuo (64.87672°N, 26.83599°E; Fig. 1), peat extraction began in 2010 and is planned to continue for at least 20 years. This open site covers an area of approximately 2.1 km^2. Cutoff ditches have been dug around the site to prevent external water entering the extraction area and the site is drained with 1 m wide open ditches dug at 20 m spacing. The drainage system is equipped with a flow control structure to reduce the peak flow and thus prevent the transport of suspended solids (SS) and associated elements (Kløve 2000, Marttila and Kløve 2010). All drainage water is diverted to a sedimentation basin, from where it is pumped to treatment wetlands. Under normal flow conditions, water leaves the peat extraction area through a pumping station. Precipitation data for the peat extraction area in this study were obtained from the Särki-

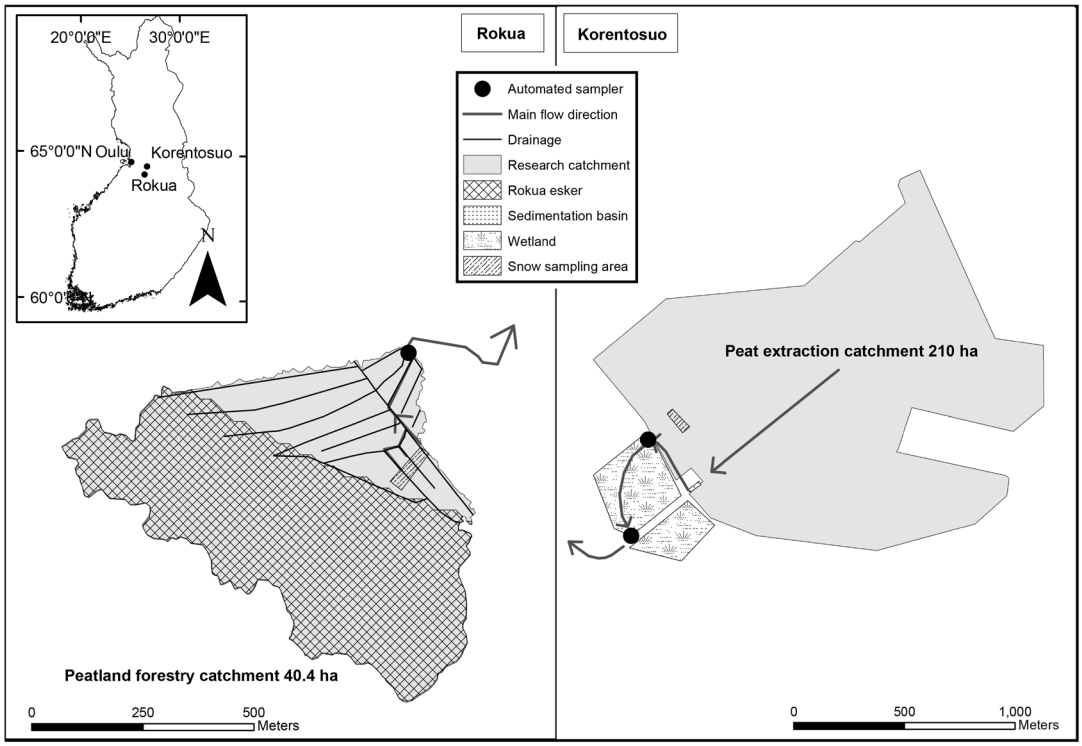

Fig. 1. Map of study areas and their locations in Finland.

järvi weather station, located approximately 20 km NE of the study area (data from the Finnish Meteorological Institute).

The peatland forestry area (64.57138°N, 26.55731°E) is located next to the Rokua esker (Fig. 1), where groundwater flows outward from the esker to the surrounding peatlands. Nearly all of the surrounding peatlands in the vicinity of the esker have been drained to promote forestry, agriculture or peat extraction. Peat thickness around the esker can be up to 7 m (Rossi *et al*. 2012). One sub-catchment was selected as the study area from among the total of 23 catchments surrounding the Rokua esker. The selected peatland forestry catchment had a surface area of 40.4 ha, of which 13 ha was drained peatland and 27.4 ha was located on the esker. The drained part of the peatland forestry catchment is served by approximately 1 m wide ditches dug at 20 m spacing. Large collector ditches connect the area to the Siirasoja stream, which then discharges into the Oulujoki. Pine (*Pinus sylvestris*) accounts for the majority of the tree stand in the research area (78%), while birch (*Betula pendula*, *Betula pubescens*) and spruce (*Picea abies*) contribute 16% and 5%, respectively. Most of the forest is mature (one-third is ready to be harvested) and new seedlings (< 1.3 m tall) account for 2% of the tree stand. On average, the tree volume per hectare is 69 m^3. Precipitation data for the peatland forestry area for this study were obtained from Pelso weather station, located approximately 10 km SW of the study area (data from the Finnish Meteorological Institute).

The hydraulic conductivity in the peat extraction area was between 5.3×10^{-9} and 2.7×10^{-8} m s^{-1} measured under laboratory conditions using a constant head permeameter. In the peatland forestry area, the hydraulic conductivity measured *in situ* by Rossi *et al*. (2012) with a falling head direct push piezometer varied between 1×10^{-5} and 1×10^{-9} m s^{-1}.

Sampling strategy

Runoff, snow and soil samples were taken at both sites using the same sampling schedule. Runoff

was sampled twice daily (05:00 and 17:00 hours) using an automated water sampler from a ditch near a V-notch weir. In the peatland forestry area, the sampler was located 5 m upstream from the V-notch weir used for flow measurements, while in the peat extraction area it was located approximately 400 m upstream from the V-notch weir. Sampling began on 15 March 2012 and continued until 31 May 2012, in order to ensure that enough samples were taken from baseflow before and after the snowmelt pulse in April. Some samples were lost due to malfunction of the sampler caused by cold temperatures before the snowmelt pulse. An opportunity for sampling the overflow water from the sedimentation pond occurred during the maximum snowmelt peak. This provided new information, as such events are rarely captured during normal water quality sampling routines.

In order to study the snow processes occurring during snowmelt, the snow was sampled half-way between the ditches and adjacent to the ditches at both study sites. For analytical purposes and to minimise sampling error, each sampling was repeated three times in both study areas. In each snow sampling location, snow was sampled from four different depths (Fig. 1). The selected layer thickness was related to the overall thickness of the sampled snowpack, each layer representing 25% of the overall snowpack depth. Snow sampling was carried out once a week with a plastic scoop until no snow was present in the sampling pit. The samples were stored in airtight zip-lock bags. On arrival at the laboratory, the samples were melted in a cold room (10 °C), immediately transferred to 50–150 ml HDPE bottles and stored in a refrigerator (4 °C) until analysis. Snow water equivalent (SWE) was measured at three different locations by weighing a snow tube with known sample volume.

Soil samples were taken from both sites during the snow cover period. In the peatland forestry area, sampling was carried out with a shovel from below the snowpack from a depth of 20 cm, since no soil frost was present. In the peat extraction area, sampling was carried out with an excavator, since the soil was frozen to 45 cm depth. Soil samples were stored in watertight zip-lock plastic bags in a refrigerator (4 °C) until completely melted. Soil porewater was then extracted by a centrifuge. Extracted porewater was stored at 4 °C in the refrigerator until analysis.

Sample analysis

All snow, stream water and soil porewater samples were analysed for stable isotope ^{18}O using a Picarro L2120i isotope analyser. The results were expressed using δ-notation relative to the Vienna standard mean ocean water (VSMOW). The precision of $\delta^{18}O$ measurement was 0.1‰.

Stream water samples and extracted soil porewater were analysed in the laboratory for pH, electric conductivity (EC), suspended solids (SS, 0.4 μm filtration, Whatman Nuclepore), colour and turbidity. After the water quality analysis, all samples were stored frozen (–20 °C) until further analysis. A selected batch of frozen samples was analysed at SYKE in January 2013 for total dissolved nitrogen (TDN), ammonium (NH_4-N, nitrate-nitrite ($NO_{2\text{-}3}$-N), total dissolved phosphorus (TDP), phosphate phosphorus (PO_4-P), dissolved organic carbon (DOC), silica (SiO_2), iron (Fe) and aluminium (Al). As all samples were filtered through a 0.4 μm filter, only dissolved forms of these elements were analysed. Water quality was analysed according to standard (SFS and ISO) analytical methods.

Many of the water quality variables showed non-normal distributions, and therefore the statistical tests were performed using bootstrap (e.g. Efron and Tibshirani, 1986). The diurnal changes in water quality were compared by placing the observed concentrations of a particular variable into the same bin, from which 10 000 samples were drawn with replacement. The drawn samples were then attached to two groups according to their original sample size. After forming the groups, the difference in a particular parameter (in this case: mean) was compared with the difference observed within the original concentrations. The acquired p value represents the likelihood of drawing a larger than observed difference from the bootstrap distribution. Analysis of variance was performed with the Ansari-Bradley test. The snow isotope values were considered to be normally distributed and therefore analysed with a t-test, an F-test and one-way ANOVA. All statistical analyses were

performed using the R software (R Development Core Team 2014).

End-member mixing analysis

To estimate the quantity of snowmelt water in streams during the snowmelt event, a hydrograph separation method based on the mass balances of water and tracer fluxes was applied:

$$Q_R = Q_T[(\delta_T - \delta_S)/(\delta_R - \delta_S)] \quad (1)$$

where Q_R is the snowmelt component of streamflow, Q_T is the measured discharge, δ_T is the tracer content of streamflow, δ_S is the tracer content of pre-event water, δ_R is the tracer content of snowmelt

This approach was used at both sites using EC, SiO_2 and $\delta^{18}O$ as tracers. For SiO_2-based separation in the peatland forestry area, a weighted mean of SiO_2 concentration in groundwater was selected to represent the pre-event water. Weighted mean was calculated using analytical results from groundwater below the peat layer (n = 7, mean 16.7 mg l^{-1}) and a nearby groundwater pipe located in the esker area layer (n = 10, mean 8.1 mg l^{-1}) (Table 1). Both means were then weighted according to the surface area they occupied within the catchment (13 ha and 27.4 ha), resulting 10.9 mg l^{-1} as the concentration of pre-event water. The SiO_2 concentration in snow was assumed to be zero. Hydrograph separation in the peat extraction area with EC as a tracer used porewater sample as δ_S (105.9 μS cm^{-1}) and the mean ± SD EC of 13 snow samples taken during the snowmelt period as δ_R (11.3 ± 5.73 μS cm^{-1}). In isotopic hydrograph separation, δ_S in the peatland forestry area was represented by a regional groundwater $\delta^{18}O$ value measured in a nearby groundwater well (–13.5‰), while δ_S in the peat extraction area was represented by a soil porewater sample extracted from below the soil frost (–12.3‰). At both sites, δ_R was represented by recorded isotope values in water discharging from snowpack.

Results

Accumulation and melt of snowpack and soil frost conditions

The snow accumulated quite evenly in the forested area, whereas in the peat extraction area it partly drifted to the ditches, leaving the area between them with less snow. SWE reached 176 mm during the snow accumulation phase in the peatland forestry area, while in the peat extraction area the measured SWE was up to 99 mm mid-way between ditches and up to 217 mm adjacent to ditches. The observed SWE maximum in the peatland forestry area was similar to that observed by local authorities (174 mm) at the nearby Oulujärvi-Vaala measuring point on 1 April 2012 (data from the OIVA database of Finland's Environment Administration). The peatland forestry area had higher concentrations of N (450 μg l^{-1}) and P (12.5 μg l^{-1}) in the snow than the peat extraction area (N = 285 μg l^{-1}, P < 3 μg l^{-1}). The observed differences were not statistically tested due to the low number of samples (n = 2, each site). Differences in the P and N contents in snow can be caused by different deposition rates, as forests have been noted to deposit about twice as much as clearings (Hicks 2006).

The melt rate of the snow varied between the different land use types. In the peat extrac-

Table 1. Mean values of water quality parameters measured in samples taken from groundwater (GW) pipes near the peatland forestry area, 2009–2012.

	GW pipe in sand layer	GW pipe in peat layer	GW pipe in the esker
n	7	10	10
EC (mS m^{-1})	8.4	5.3	2.0
SiO_2 (mg l^{-1})	16.7	3.72	8.1
$NO_{2\text{-}3}N$ (μg l^{-1})	87.7	7.4	< 5
PO_4-P (μg l^{-1})	120	26.9	27.4
$\delta^{18}O$ (‰)	–13.5 (n = 9)	–13.0 (n = 12)	–13.2 (n = 10)

tion area snowmelt occurred rapidly: on 23 April 2012 mean measured snow cover was 47 cm but seven days later (30 April) there were just a few spots of snow left, mainly in the ditches. In the peatland forestry area, snow depth started to decline on 10 April but 24 days later (6 May) there were still some spots of snow left. Thus the mean melt rate was 23 mm d^{-1} and 8 mm d^{-1} in the peat extraction and forestry areas, respectively. These melt rates resulted in a degree-day factor of 6.1 mm $°C^{-1}$ d^{-1} for the peat extraction area and 3.8 mm $°C^{-1}$ d^{-1} for the peatland forestry area, which is equal to or higher than values obtained by Kuusisto (1980) for agricultural fields and clearings without forest cover (mean = 3.7 mm $°C^{-1}$ d^{-1}).

In the peatland forestry area, the absence of soil frost was identified by pushing a shovel blade into the peat. In the peat extraction area, it should be noted that soil frost was measured in one location. In a recent study of the treatment wetland of the same peat extraction area during winter 2009–2010 and 2010–2011 (Postila *et al*. 2011), the soil frost extended on average to 30 cm and 20 cm, respectively. The observed soil frost depth (45 cm) in the peat extraction area in the present study was comparable to that observed in mineral soils (sand, silt and moraine) at similar latitude (Soveri and Varjo 1977, Korhonen and Haavanlammi 2012).

Snow isotopes

The isotope signatures in snow differed between study areas. All the snow samples collected from each site were significantly different in terms of $\delta^{18}O$ content (*t*-test: $t = 1.9828$, df = 264.596, $p = 0.04842$) while the variances were not (*F*-test: $F = 0.65417$, df = 142, $p = 0.05842$). The snow in the peat extraction area had a wider range of $\delta^{18}O$ values than that in the peatland forestry area (Table 2). No significant differences were found between the six snow sampling locations at each site (one-way ANOVA, peatland forestry area: $F_{5,194} = 0.741$, $p = 0.593$; peat extraction area: $F_{5,137} = 1.297$, $p = 0.269$). The overall range of $\delta^{18}O$ values in all snow samples ($n = 373$) was from –10.5‰ to –23.5‰ (Table 2). The value measured in meltwater originating from snowpack in the peat extraction area (mean $\delta^{18}O$ = –15.5‰, $n = 4$) was quite close to the mean value in snowpack on 23 April 2012 ($\delta^{18}O$ = –16.3‰).

Table 2. Results of soil porewater and snow analyses.

	Peatland forestry area		Peat extraction area	
	Porewater	Snow	Porewater	Snow
n	1	203	1	153
EC (μS cm^{-1})	227		105.9	
pH	4.6		5.9	
Colour (Pt mg l^{-1})	550		200	
$\delta^{18}O$ (‰)	–12.8	mean: –16.7, min: –21.3, max: –13.0	–12.3	mean: –17.1, min: –23.5, max: –10.5
DOC (mg l^{-1})	200		68	
N (μg l^{-1})	17000		10000	
$NO_{2\text{-}3}N$ (μg l^{-1})	390		250	
NH_4N (μg l^{-1})	8800		3600	
P (μg l^{-1})	690		310	
PO_4P (μg l^{-1})	270		200	
Fe (μg l^{-1})	1700		190	
SiO_2 (mg l^{-1})	2.8		7.3	
Al (μg l^{-1})	580		990	
Ba (μg l^{-1})	210		6.4	
Mn (μg l^{-1})	360		9.6	
Sr (μg l^{-1})	140		6.4	
Ti (μg l^{-1})	5.4		2.8	

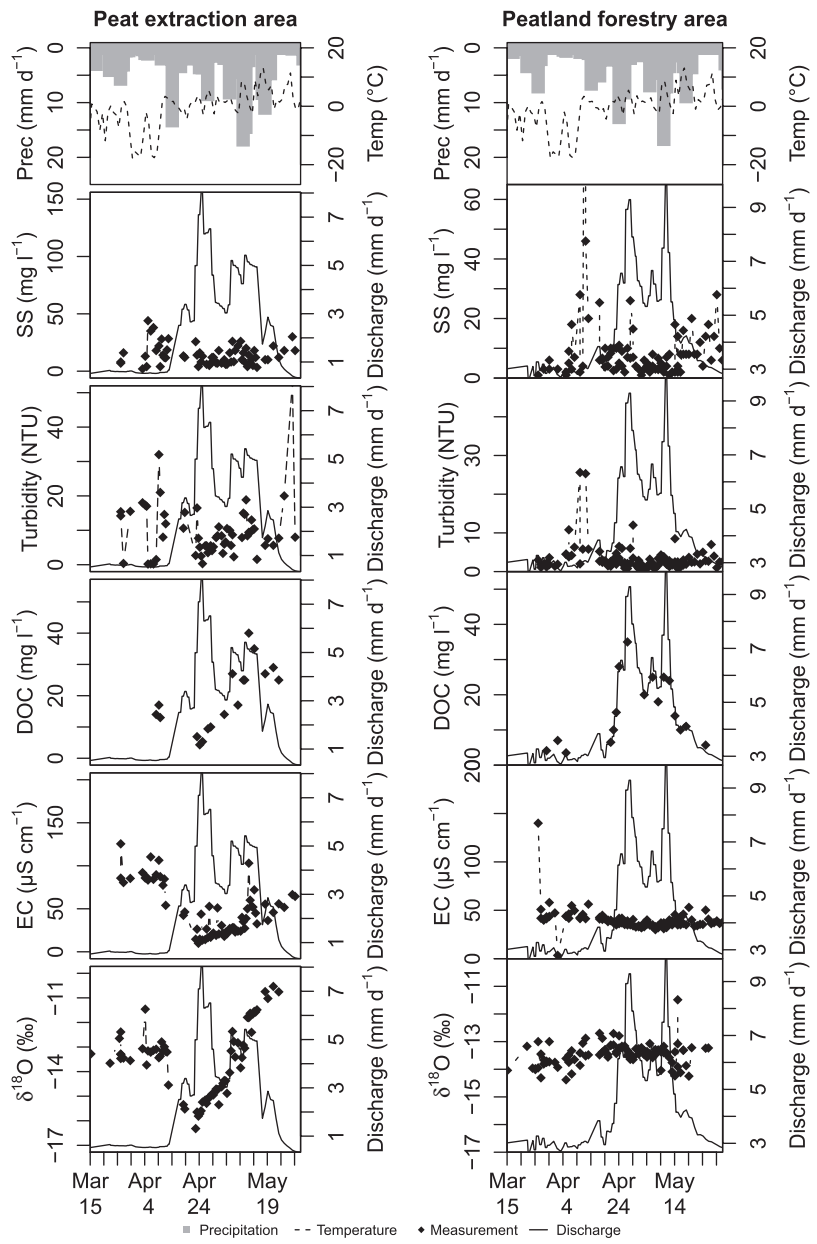

Fig. 2. Precipitation, temperature, water quality measurements and discharge during the snowmelt period in the peatland forestry and peat extraction areas.

Characteristics of runoff during snowmelt

The leachate from the peat extraction and forestry areas differed in terms of water colour, $\delta^{18}O$, EC and DOC (Fig. 2). The concentrations of all these variables showed a clear decrease during maximum snowmelt runoff in the peat extraction area, while most concentrations remained stable or increased with increasing flow in the peatland forestry area. The rest of the water quality results are shown in Appendix 1. The hydrograph separations performed with SiO_2 and EC showed that a large proportion of stream discharge consisted of event water for both sites during the snowmelt event (Fig. 3). Uncertainty estimations for hydrograph separations carried out as described by Genereux (1998) resulted in a mean uncertainty of 11% ± 3% (SD) for SiO_2 and 8% ± 4% (SD) for EC. With isotopic hydro-

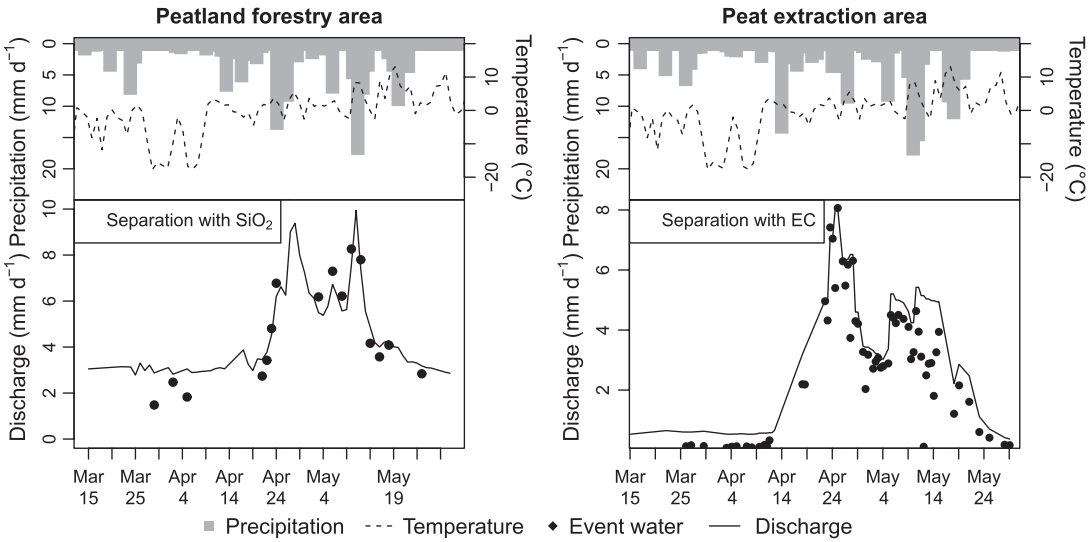

Fig. 3. Precipitation, temperature and (lower section), event water and discharge for the snowmelt period in the peatland forestry and peat extraction areas. Mean ± SD uncertainties for the event water using Genereux (1998) method for SiO_2 and EC were 11% ± 3% and 8% ± 4%, respectively.

graph separation, the uncertainty was higher and therefore not included in further analysis (±42% for peatland forestry area and ±50% for the peat extraction area on average). However the isotopic values measured at the outlet of both sites showed a difference: the peat extraction area displayed a clear response to the snowmelt event, while no clear sign of a snowmelt pulse was visible in the peatland forestry area.

The maximum snowmelt peak occurred three days later in the peatland forestry area than in the peat extraction area. A similar difference in timing between peat extraction and forested areas has been reported by Ketcheson *et al*. (2012). Both sites showed a similar pattern in transport of SS, which reached its highest peak before the maximum flow peak (Fig. 2) and can be attributed to first flush of sediments (e.g. Marttila and Kløve 2008, 2010). Similar peaks were seen in turbidity, which is often used as a proxy for SS content (e.g. Gippel 1995, Packman *et al*. 1999).

Diurnal variation in water quality

A diurnal variation in SS was found at the peat extraction area when comparing morning (05:00) and evening (17:00) samples taken on the same day. This was seen as a significant difference (bootstrap p = 0.0007) in SS between water samples taken in the peat extraction area in the morning (mean SS = 8.6 mg l^{-1}) and evening (mean SS = 16.2 mg l^{-1}) (Appendix 2). This indicates that there can be considerable variation in SS concentration during a single day. No significant differences were found between daily values of EC, pH or colour. In the peatland forestry area, the mean concentrations and their variance were not significantly different in the morning and evening samples.

Soil porewater

The analyses of the extracted soil porewater samples indicated differences between the study areas (Table 2). The concentration of DOC was 200 mg l^{-1} for the peatland forestry area and 68 mg l^{-1} for the peat extraction area. The peat extraction area had a higher quantity of SiO_2 than the peatland forestry area, which could be a sign of groundwater contact. The differences within the observed concentrations can be due to different land uses, different sampling depths or spatial variance.

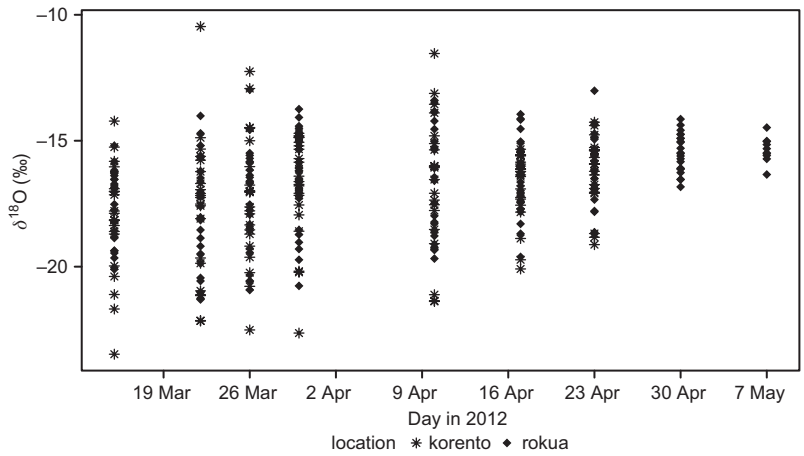

Fig. 4. Temporal variations in $\delta^{18}O$ values in the peat extraction and peatland forestry areas.

Discussion

Snowpack dynamics

Variance in the snowpack isotope values decreased from the beginning of the sampling period until snowmelt (Fig. 4). This is most likely explained by the ripening process, where different layers of snow intermingle due to melting and refreezing processes occurring in spring with diurnal variations in temperature before runoff is formed. Similarly, Taylor *et al*. (2001) reported that the isotopic composition of snowpack tends to homogenise from the early accumulation phase to the snowmelt period. The mean $\delta^{18}O$ value in snowpack increased during ripening of the snowpack, from –17.9‰ to –15.5‰. A similar increase has been reported by Taylor *et al*. (2001) and Unnikrishna *et al*. (2002).

Effect of soil frost on runoff processes and leaching of elements

There was a clear difference between the flow paths and transport of elements in the forestry and peat extraction areas. The presence of a large groundwater body and a thick insulating snow layer prevented formation of soil frost in the peatland forest. The spring melt peak at the forestry site was rich in colour and DOC, which indicates that water released from snowmelt infiltrated into the soil and flushed out old water rich in humic substances. The concentrations of Fe, Mn, TDP and TDN also increased in the stream, while SiO_2 concentration decreased (Appendix 1).

The SiO_2-based hydrograph separation for the peatland forestry area showed that groundwater represented approximately 10% of the runoff during the snowmelt pulse. Calculating the stream water $\delta^{18}O$ value by using the mixing ratio given by the SiO_2 separation produced a value of –15.3‰. However as seen in Fig. 2, the $\delta^{18}O$ value remained relatively stable at –13.7‰. This indicates that the meltwater pulse mobilised soil water from the peat layer with low silica concentration and $\delta^{18}O$ value similar to the local groundwater (Table 1). The results of soil porewater analysis supported the hypothesis of snowmelt moving through the peat soil layer in the peatland forestry area, as it was frost free. It is obvious that the increased amounts of colour, DOC, Fe, Mn TDP and TDN must have originated from the soil porewater within the peat layer, since they were not present in large quantities in groundwater samples from the Rokua esker area (Table 1), except for P, in which the Rokua sand aquifer is naturally rich (Ala-aho *et al*. 2013). The high uncertainties associated with the isotope hydrograph separation method for the peatland forestry area were most likely caused by the similar $\delta^{18}O$ value within the local groundwater and the water stored in the peat layer (the assumption that the waters to be separated are different enough was not satisfied). Moreover, at both sites there were not enough samples from the meltwater originating from the snowpack.

In the peat extraction area, the frost penetrated down to 45 cm from the soil surface, which prevented snowmelt infiltration and caused overland flow on the frozen soil surface. Due to the frozen soil, the concentration of DOC decreased during the snowmelt peak. The hydrograph separation showed snowmelt to be the dominant source of runoff. In the peat extraction area, the runoff peak was almost entirely caused by snowmelt, whereas in the peatland forestry area the snowmelt peak was from pre-event soil water. Our observations support the visual observations by Ketcheson *et al*. (2012) of meltwater forming visible ponds on frozen soil in peat extraction areas. Our results demonstrate that snowmelt runoff varies between different peatland uses and that soil warming by groundwater can prevent ground frost in drained areas influencing water quality in snowmelt events.

Effect of snowmelt on water quality variation

The main finding of this study is the impact of soil frost on runoff water quality. In the peat extraction area with soil frost, the water was low in dissolved substances during the maximum snowmelt runoff, whereas the opposite was observed in the peatland forestry area. Buffam *et al*. (2007) observed similar behaviour between a forested catchment and wetland-dominated catchment. They attributed this to a shift in water flow paths from mineral soil to upper organic soils in forested catchments and dilution of peat water in wetland-dominated catchments. In the present study, analysis of flood water (Table 3), soil porewater (Table 2) and runoff water quality in the drainage network (Fig. 2) showed that soil frost prevented the meltwater from interacting with the soil matrix and soil water stores in the peat extraction area, thus preventing leaching of elements from the peat. After the maximum flow peak was reached, the concentrations of most elements started to increase (Fig. 2). In particular, colour and DOC reached their minimum values shortly after the flood peak, but EC, pH, NH_4-N, TDN, TDP, Mn, and Fe values slowly increased towards their pre-event values. We attributed this to melting soil frost and infiltra-

Table 3. Summary of analyses of water samples taken between 15 March and 31 May 2012. '<' before a value indicates value below the detection limit.

	Peatland forestry area				Peat extraction area				Flood water[a] (n = 1)
	Min	Max	Mean	n	Min	Max	Mean	n	
EC (μS cm^{-1})	30	58	39.1	98	9.9	125.5	48.7	65	10.3
pH	5.1	7.3	–	98	5.3	7.4	–	65	6
Colour (Pt mg l^{-1})	20	300	125.8	98	30	400	161.7	65	40
δ^{18}O (‰)	–14.4	–11.5	–13.5	94	–16.3	–10.5	–13.6	69	–15.5
DOC (mg l^{-1})	3.5	35	15.4	17	4.3	40	19.1	18	
SS (mg l^{-1})	1	249.3	10.8	89	2	44	14	65	4
Turbidity (NTU)	0.6	25.6	3.4	98	1.56	53	10.8	61	1.6
N (μg l^{-1})	430	3200	1041	17	980	4200	2303	18	
$NO_{2\text{-}3}$N (μg l^{-1})	7	79	36.9	17	53	290	115.2	18	
NH_4N (μg l^{-1})	55	560	199.2	17	260	2100	1054	18	
P (μg l^{-1})	11	31	18	17	4	58	22.2	18	
PO_4P (μg l^{-1})	< 2	8	1.9	17	< 2	26	5.6	18	
Fe (μg l^{-1})	140	990	471.2	17	74	2000	804	17	
SiO_2 (mg l^{-1})	1.4	10	4.4	17	0.7	20	14.9	4	
Al (μg l^{-1})	16	120	85.3	3	47	270	195.7	3	
Ba (μg l^{-1})	36	46	41.7	3	6.5	15	9.3	3	
Mn (μg l^{-1})	< 1	52	24.8	17	14	180	61.2	17	
Sr (μg l^{-1})	18	23	21	3	5.6	29	13.7	3	
Ti (μg l^{-1})	< 1	1.3	1.0	3	< 1	2.3	1.6	3	
Zn (μg l^{-1})	11	16	13	3	33	58	42.7	3	

[a] sample taken from flood water in the peat extraction area.

tion of meltwater into soil layers, which pushed old soil water out to the ditch network. At first, the water from the quickly melting snow presumably moved in frozen ditches and was not able to leach dissolved/particulate matter from the peat, but as snowmelt proceeded the soil frost melted, leading to an increase in concentration of different elements. The diurnal water sampling allowed us to study water quality differences between the daily maximum and minimum snow melt, to see whether higher daytime temperatures led to changes in water quality. There was a difference between morning and evening runoff water samples during snowmelt: SS concentration was significantly higher in the samples taken in the early evening in the peat extraction area (*see* section 'Diurnal variation in water quality' in the results). This may originate from increased flow velocity due to increased water quantity in the ditches caused by higher melt rate during the day, leading to increased erosion and transport capacity of SS in ditches. Another explanation could be that the cold temperature during the night partially froze the water melted during the day, which would also trap the particulates from the water to the ice, giving a lower concentration in the morning samples.

In a study on the effect of climate change on snow cover, soil moisture and soil frost, Kellomäki *et al*. (2010) concluded that the soil frost layer in southern Finland will be thinner in the future. As shown in the present study, soil frost can have an impact on water quality and therefore the national environmental policies related to water quality should take into account regional climate conditions instead of using one national standard throughout the country. For example, different water treatment policies could be used in areas where seasonal soil frost is common and in areas where soil frost is rare, leading to improvements in downstream water quality and more cost-effective water treatment solutions.

Conclusions

Snow accumulation and snowmelt generation were studied in two different peatland sites with different land uses during the spring runoff period in a cold climate region (northern Finland). These peat extraction and peatland forestry areas were found to have different patterns of snow accumulation and melt. In the peat extraction area, snow depth was more variable and lower than at the forested site due to snow drift to ditches. Faster snowmelt was observed in the peat extraction area than in the forested area, resulting in degree-day factors of 6.1 and 3.8 mm $°C^{-1}$ d^{-1}, respectively.

The water isotope and water quality analyses of diurnal stream water samples provided evidence of the role of local soil frost on runoff generation and runoff water quality. Soil frost hindered the infiltration of melt water into the soil, generating more overland flow which was low in concentrations of dissolved elements and organic matter. At the site with soil frost, the stable water isotope ^{18}O in runoff was depleted, as in the snow, indicating snowpack as the primary source of runoff. At the site without frost, snowmelt water infiltrated into the soil, pushing out older water and increasing the amount of humic substances and suspended solids in runoff. As the old water in the soil had similar isotopic composition to the local groundwater, no response in the water isotope values was observed.

Peatlands are mainly seasonally frozen in the cold climate region of northern Finland, whereas frost-free peatlands can be found in more temperate climates. However, locally in cold climate regions groundwater discharge can reduce soil frost. Therefore peatland areas located next to groundwater bodies can make a larger contribution to the transportation of organic matter than previously thought. Additional studies of these areas could help develop better models for estimating the amount of transported DOC and SS on catchment scale. Climate change will have an effect on frost depth in cold climate regions due to increased air temperature and changes in precipitation patterns. Therefore climate change can be a potential cause of changes in runoff water quality in peatland areas in future.

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Appendix 1

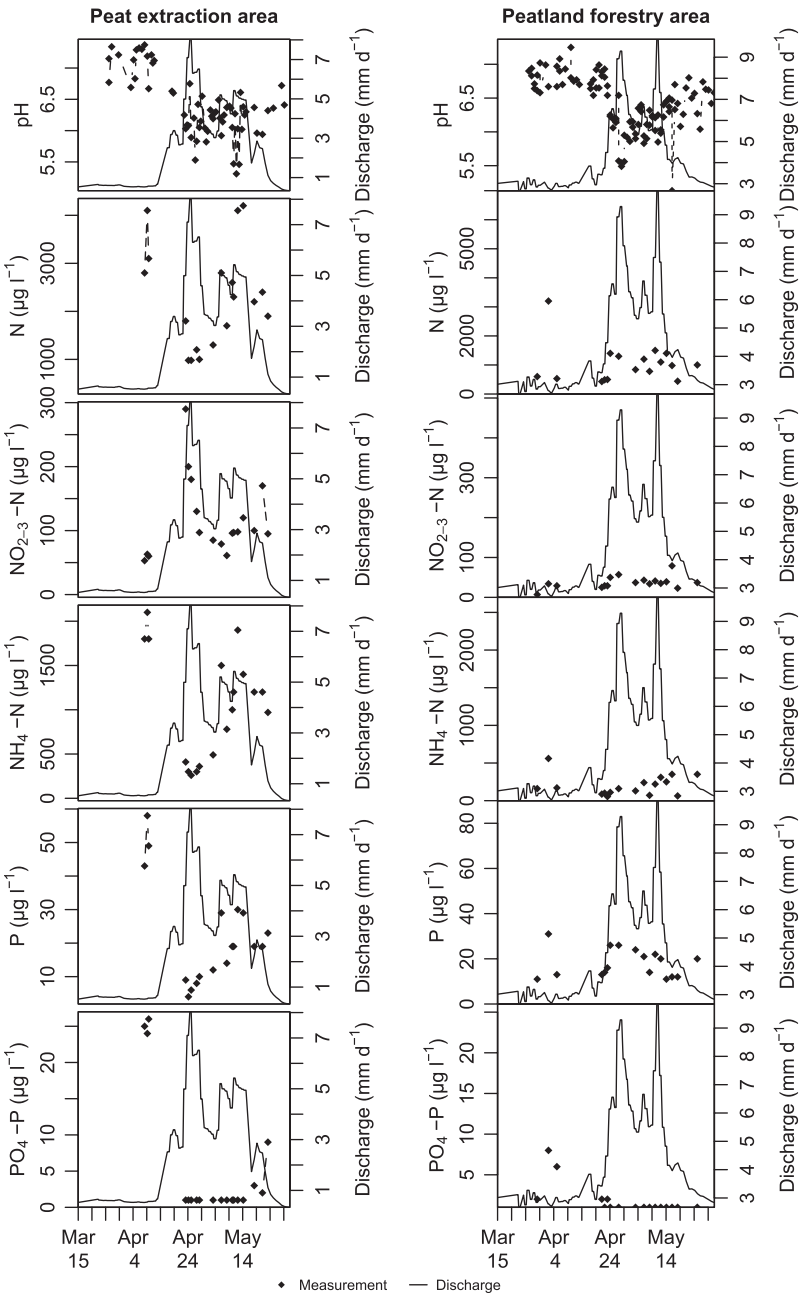

Fig. A1_1. Water quality parameters and discharge during the snowmelt period in the peatland forestry and peat extraction areas.

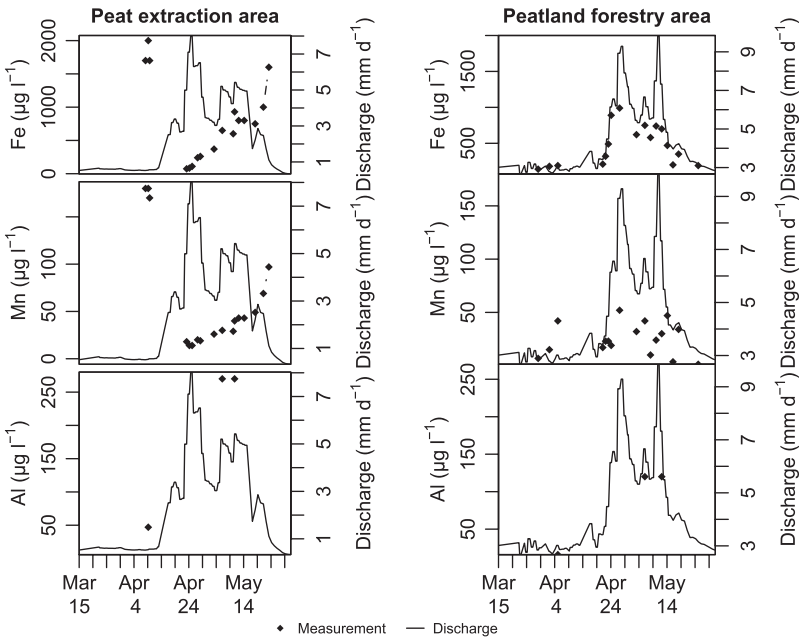

Fig. A1_2. Water quality parameters and discharge during the snowmelt period in the peatland forestry and peat extraction areas.

Appendix 2

Results of the statistical analysis of the peatland forestry and peat extraction areas and the means and variances of the tested samples. Number of pairs describes the sample size included in tests, morning and evening samples recorded on same date were selected for testing. The difference between mean values in morning and evening samples was studied with the bootstrap method, drawing 10 000 samples to form the bootstrap distribution.

	Bootstrap *p*	Ansari-Bradley test	Number of pairs	Mean		Variance	
				morning	evening	morning	evening
Peatland forestry area							
SS (mg l^{-1})	0.708	$p = 0.2158$, AB = 394.5	29	15.6	8.5	2060.9	81.4
Turbidity (NTU)	0.3419	$p = 0.5718$, AB = 606	35	3.6	2.7	20.7	3
EC (μS cm^{-1})	0.3872	$p = 0.6975$, AB = 646.5	35	37.8	38.8	19.2	26.7
pH	0.6699	$p = 0.9064$, AB = 625	35	6.4	6.4	0.2	0.2
Colour (Pt mg l^{-1})	0.9163	$p = 0.4817$, AB = 660.5	35	150	152.3	7304.4	8497.6
Peat extraction area							
SS (mg l^{-1})	0.0007	$p = 0.4776$, AB = 223	20	8.6	16.2	25.4	80.2
Turbidity (NTU)	0.3451	$p = 0.08435$, AB = 178	17	7.5	9	15.4	30
EC (μS cm^{-1})	0.8298	$p = 0.4208$, AB = 204	19	39.8	38	434.9	757.8
pH	0.4011	$p = 0.8606$, AB = 187	19	6.1	6.3	0.2	0.1
Colour (Pt mg l^{-1})	0.9622	$p = 0.6566$, AB = 197.5	18	167.4	169.5	12170.5	14174.7